WADC TECHNICAL REPORT 52-322, Part 1

CAUSES OF CRACKING IN HIGH-STRENGTH WELD METALS

A. J. WILLIAMS
A. J. JACOBS
P. J. RIEPPEL
C. B. VOLDRICH

BATTELLE MEMORIAL INSTITUTE

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Statement A
Approved for Public Release

WRIGHT AIR DEVELOPMENT CENTER

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A. J. Williams
A. J. Jacobs
P. J. Rieppel
C. B. Voldrich

Battelle Memorial Institute

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Wright Air Development Center
Air Research and Development Command
United States Air Force
Wright-Patterson Air Force Base, Ohio

FOREWORD

This report was prepared by the Battelle Memorial Institute under U. S. Air Force Contract No. AF 33(038)-12619. The contract was initiated under Research and Development Order No. 615-20, "Welding of Metals," and was administered under the direction of the Materials Laboratory, Directorate of Research, Wright Air Development Center, with Major Robert E. Bowman and Major L. P. Marking acting as project engineers. This report is the second to be issued on this project; the first report was WADC Technical Report 52-143, "Literature Survey on Weld-Metal Cracking." Additional reports will be issued as the research progresses.

ABSTRACT

In this investigation, the major part of the effort was devoted to making and testing a special apparatus for determining the hot ductility of weld metals. The apparatus was designed so that the test specimen could be tested in tension after the center section had been cooled directly from the molten state to a predetermined temperature. The center section was melted by induction heating and was retained in place by a mold of fused silica. Special equipment was designed and constructed to measure the load required to fracture the specimen and to measure the elongation. Techniques were developed to measure the temperature at the center section. The operation of the apparatus was checked by testing SAE 1018 and SAE 4340 steel specimens in the temperature range from 2588°to 1800°F after the center section was cooled directly from the melting temperature. The equipment was satisfactory and will be used in future tests to determine the effects of weld-metal composition on hot strength and hot ductility. Seven special heats of SAE43XX steels were made with different sulfur and carbon contents. These steels will be included in future tests to determine the effects of carbon and sulfur on hot strength and hot ductility.

Some studies were made with weld-metal cracking test specimens to develop a specimen that could be used in conjunction with the hot-ductility studies. Techniques were also developed for using the electron microscope in the study of grain boundaries of weld metals.

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDING GENERAL:

M. E. SORTE
Colonel, USAF
Chief, Materials Laboratory
Directorate of Research

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Causes of Cracking in High-Strength Weld Metals

The objective of this investigation is to obtain basic information on the causes of and methods of eliminating or controlling cracking in high-strength weld metals used to join high-strength alloy steels used in aircraft and other industries. At the start of the investigation, it was realized that the problems of weld-metal cracking were complex, and that an understanding of the causes of cracking and methods of prevention would require a long-range fundamental study. Therefore, this type of investigation was initiated by the Materials Laboratory at Wright-Patterson Air Force Base.

The initial step in the investigation was to survey and evaluate all literature pertaining to this problem. The survey was made and was summarized in a report dated August 11, 1951. In brief, this survey showed that many authors believe that a large part of weld-metal cracking is hot cracking which occurs during the freezing of molten weld metal and cooling on down through the plastic range to 1500 F or below. The cracking was believed to result from poor ductility at some high-temperature range and inability of the metal to adjust to stresses imposed during cooling. Little information was found concerning influence of composition, cooling rates, and stresses on hot ductility and hot cracking of high-strength weld metals. Therefore, it was decided to study hot ductility and strength of various high-strength weld metals and their relationship to alloy composition and hot cracking.

This report summarizes experimental work done during the second contract period from August 12, 1951, to August 12, 1952. It describes: (a) the development and use of apparatus for measuring the hot ductility and strength of weld metals as they cool down from the molten state; (b) a study of weld-metal cracking tests to use in conjunction with the hot-ductility studies; (c) preparation of special alloy weld metals containing known quantities of materials which influence cracking such as carbon and sulfur; and (d) a limited study of grain boundaries of a crack-sensitive weld metal by the electron microscope.

SUMMARY

The work on the various parts of this program is summarized briefly in the following:

Hot-Strength and Hot-Ductility Studies

Reports on many hot-ductility tests were found in the literature. In these tests, metal was heated from room temperature up to a testing temperature; the weld metal was never cooled down from the molten state to a testing temperature. In hot cracking, the cracks occur as the metal cools down from the molten state, so it appeared of paramount importance that hot-ductility studies be made on this cooling-down cycle. A major part of the effort during this contract period was devoted to making and proving out apparatus for this type of study.

Apparatus was designed and made with which the center section of a test bar could be melted by induction and retained in position by a mold of fused silica. The molten section was allowed to freeze and cool to a predetermined temperature and then tested in tension. Apparatus was developed to measure the load required to fracture the specimen. A special extensometer was developed to measure elongation or ductility. It was found possible to test simulated welds over a temperature range from 2600 F down to 1800 F. Separate studies were needed to develop a technique for measuring temperatures.

Several tests were made to prove out the apparatus to insure that consistent results could be obtained. Following these tests, two series of tests were conducted on SAE 1018 and SAE 4340 steel specimens in the temperature range from 2588 to 1800 F during cooling from the melting temperature. Both of these steels had little or no strength and ductility at high enough temperatures. With decreasing temperature, SAE 4340 increased in strength and ductility, but SAE 1018 became stronger but not appreciably more ductile. It appears that both steels are most crack sensitive at temperatures of 2100 F or greater. Further tests are in progress with these steels and others to check and amplify the results already obtained. The future tests will be conducted on special-purity steels which represent high-strength weld-metal compositions.

Weld-Metal Cracking Tests

Studies were made with four weld-metal cracking test specimens to find a specimen that could be used in conjunction with the hot-ductility studies. A double-vee restrained butt-joint specimen, a circular-groove specimen, a circular-patch specimen, and restrained double-fillet specimens were studied with four high-strength weld metals. None of these tests proved completely satisfactory, but results indicated that some modification of the restrained double-fillet or circular-patch specimen may be usable.

Preparation of Special Weld-Metal Compositions

Seven heats of high-purity SAE 43XX steels were made from electrolytic iron. The sulfur content ranged from 0.005 to 0.008 per cent in six of the heats. The remaining heat contained 0.037 per cent sulfur. These steels will be used to study the relaticnship between hot cracking and the sulfur and carbon contents of weld-metal composition.

Study of Grain Boundaries

The electron microscope was used to study grain boundaries of crack-sensitive and sound weld metals. The grain boundary areas of the crack-sensitive metals were more pronounced than those in the crack-insensitive metals. The cracks were found to be the transgranular as well as intergranular. These studies were limited, but techniques were developed by which the electron microscope can be used to study grain boundaries of weld metals of special interest in future studies with the hot-ductility testing apparatus.

HIGH-TEMPERATURE STRENGTH AND DUCTILITY TESTS

It was the purpose of the test to determine the tensile properties of weld-metal compositions in the temperature range 1800 F to 2600 F. The belief was that the compositions which showed certain zones of low strength and ductility would be most crack sensitive.

The literature makes no reference to tension tests made during cooling from the melting temperature. It remained to devise, therefore, a testing technique which would solve problems in rapid heating of a steel specimen, retaining molten metal, and casting so that the specimen was still in one solid piece. Methods for measuring temperature, stress, and strain also had to be developed.

Induction heating was used for two reasons. In the first place, the temperature of the measuring equipment could be kept within safe limits. Secondly, it would be possible to realize the steep temperature gradients found in an actual weld.

Equipment

The test specimen is shown in the drawing of Figure 1. A diameter of 1/2 inch was chosen, which was the same as the inner diameter of the

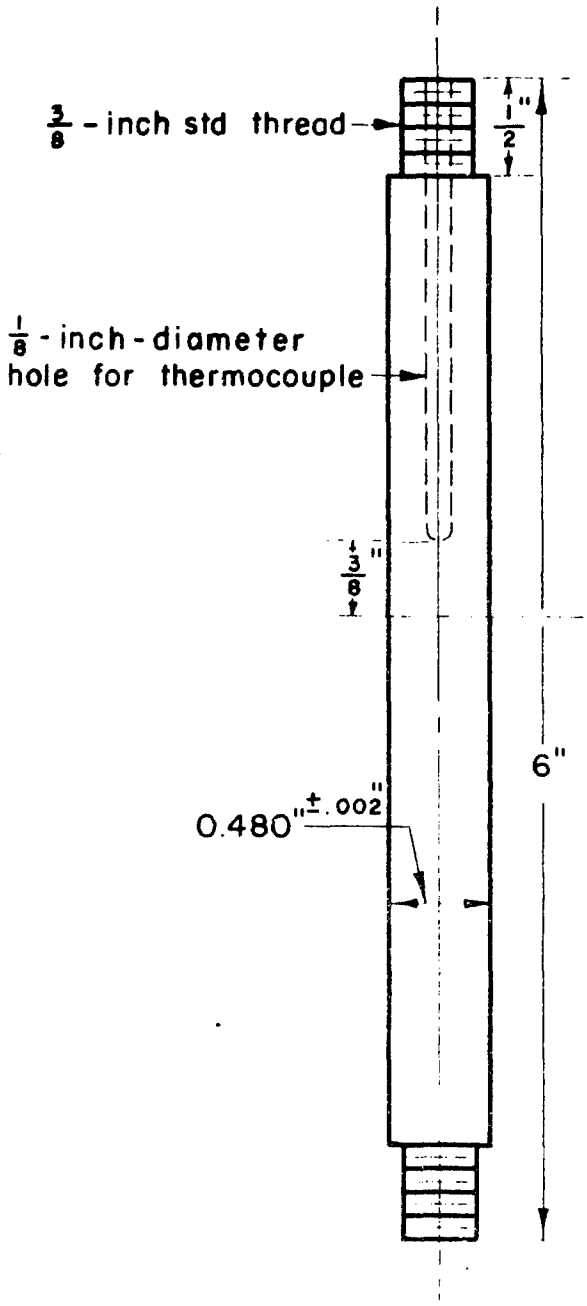

FIGURE 1. HOT-TENSION SPECIMEN

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refractory tube holding the melted metal in place, at 2700 F. The specimen was made long enough so that an extensometer affixed to both ends would not become overheated.

For induction heating, a Tocco Two-Station Unit was used with a heating coil, which was essentially a single-turn split-bar type with cooling coils attached.

Sillimanite, alumina, and fused-alumina tubing were tried in early tests as a means of retaining molten metal, but all had little resistance against thermal shock. Silica tubing was found to serve the purpose. The induction-heating assembly is shown in Figure 2. A photomacrograph of the melted zone in an SAE 4340 steel specimen is shown in Figure 3. The size of the shrinkage cavity in the center of the melted zone was discovered to depend on the type of steel tested. A controlled cooling rate may prevent the appearance of such cavities.

Several wiring changes in the Tocco Unit made it possible to operate both Stations No. 1 and No. 2 at Station No. 1. Now, by setting a timer, the heating and cooling cycles could be regulated automatically. Reproducible results were better assured.

Temperature was measured with a platinum-platinum rhodium thermocouple inserted in a hole drilled axially through one end of the specimen. After insertion, the hot junction of the thermocouple was welded to the bottom surface of the hole with a condenser-discharge welder to assure good contact with the specimen. The hot junction, as can be seen from Figure 2, falls short of the melted section, which is about 5/8 inch long. Hence, it was necessary to calibrate the thermocouple with a second thermocouple which measured the actual temperature at the midsection. This was done by inserting another platinum-platinum rhodium thermocouple in a hole drilled axially from the other end to the center of the melted zone. The calibration setup is shown in Figure 4. A wash coating of Alundum cement was used to protect the calibration thermocouple bead from the molten steel. Six calibration tests were made.

The results of the tests using SAE 4340 steel specimens are plotted in Figure 5. The true temperature corresponding to a particular reading for the test thermocouple can be read off the upper curve. When selecting the breaking temperature at the start of a run, this procedure was reversed. Another heating-cooling cycle will be tried to determine the effect on shrinkage cavities.

An air cylinder, which is controlled by a four-way solenoid valve, is used to apply load. The cylinder is able to deliver a pull of 1800 pounds, at 80 pounds air pressure. This load can rupture a 1/2-inch-diameter steel specimen at temperatures above about 1300 F. The hot-tension test assembly is shown in Figure 6.

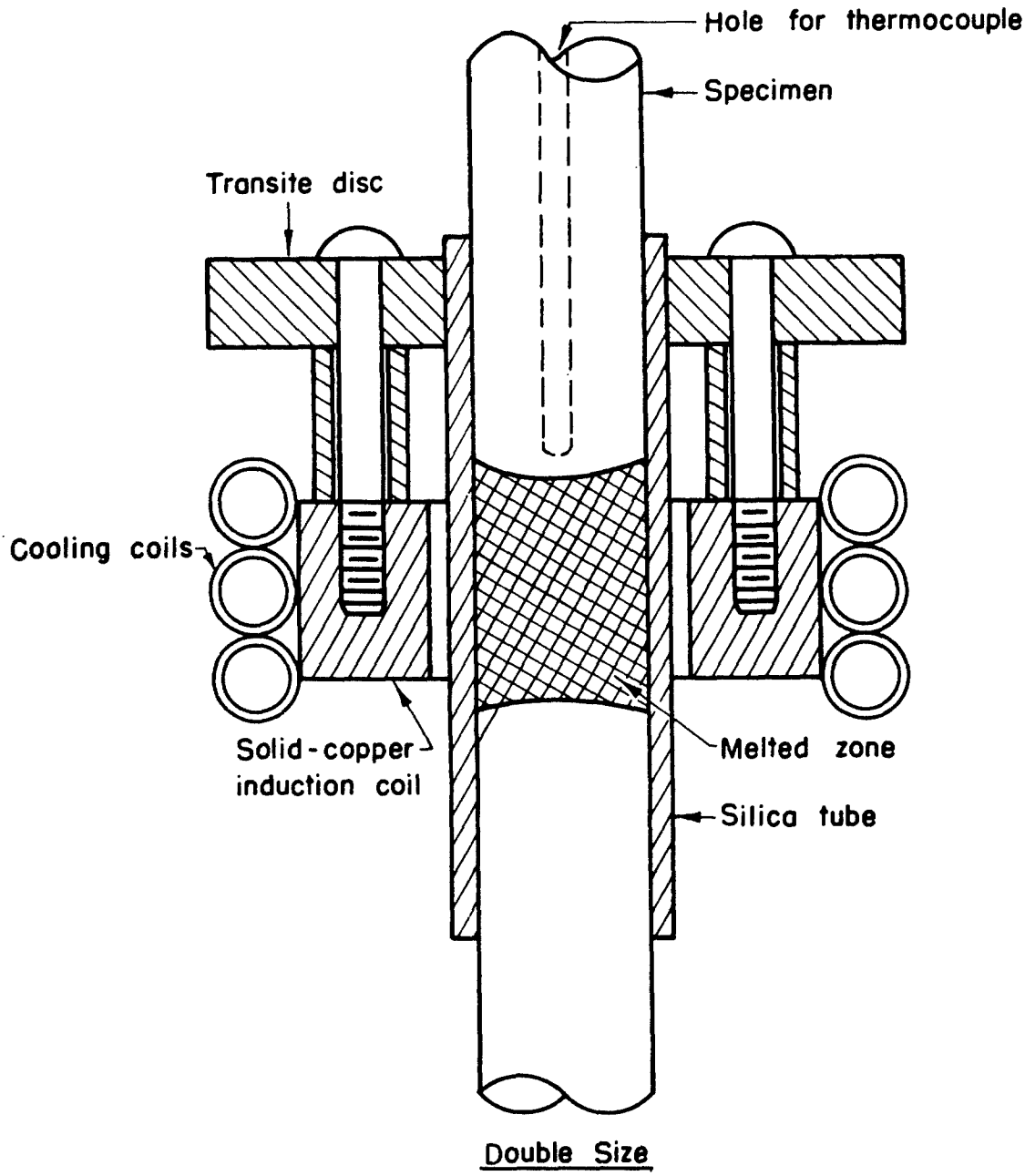

FIGURE 2. INDUCTION-COIL ARRANGEMENT AND RELATIVE SIZE OF MELTED ZONE OBTAINED

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FIGURE 3. · PHOTOMACROGRAPH OF MELTED ZONE IN AN SAE 4340 STEEL SPECIMEN SHOWING CAST STRUCTURE AND SHRINKAGE CAVITY

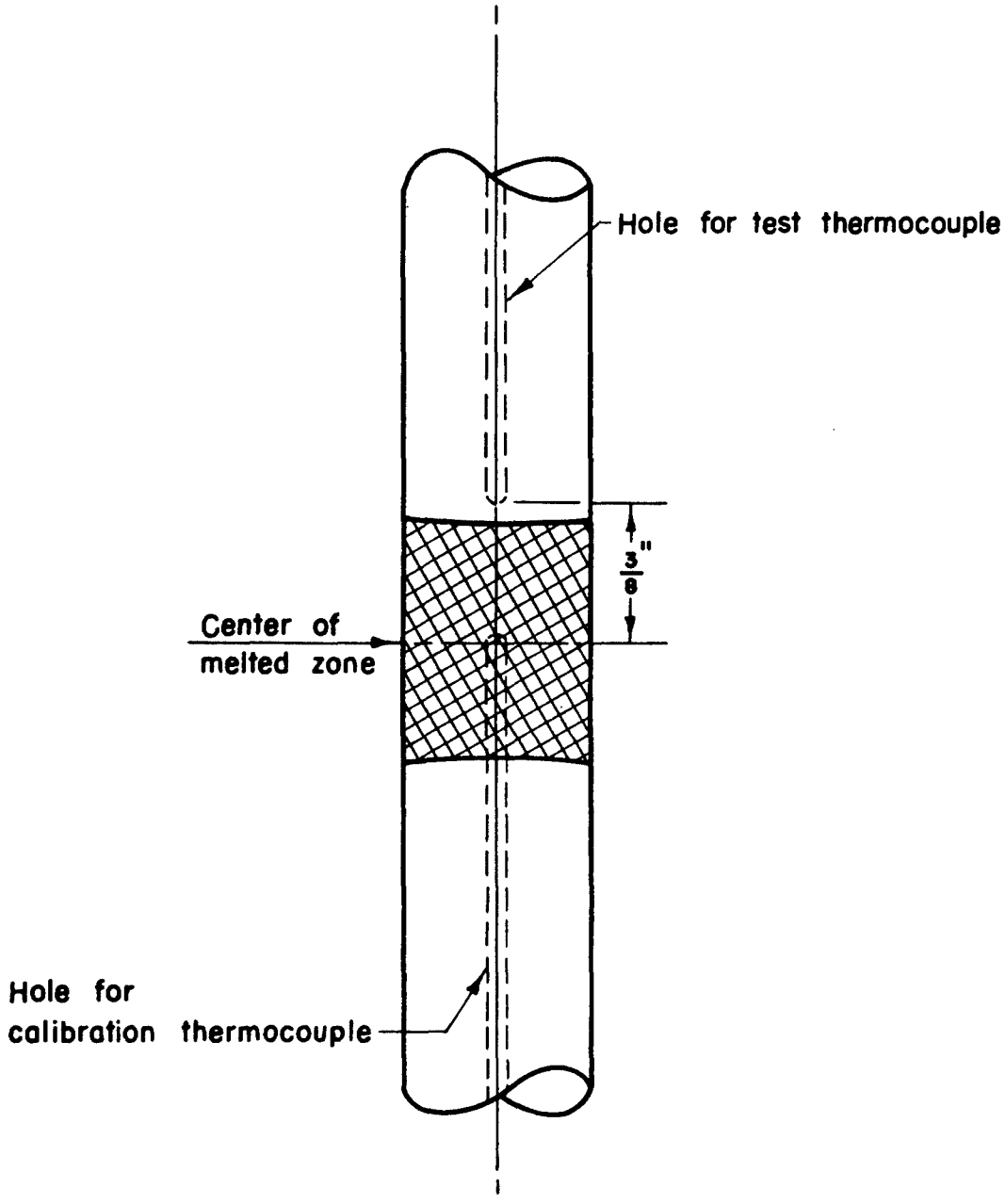

FIGURE 4. RELATIVE POSITIONS OF THERMOCOUPLES IN TEMPERATURE-CALIBRATION TESTS

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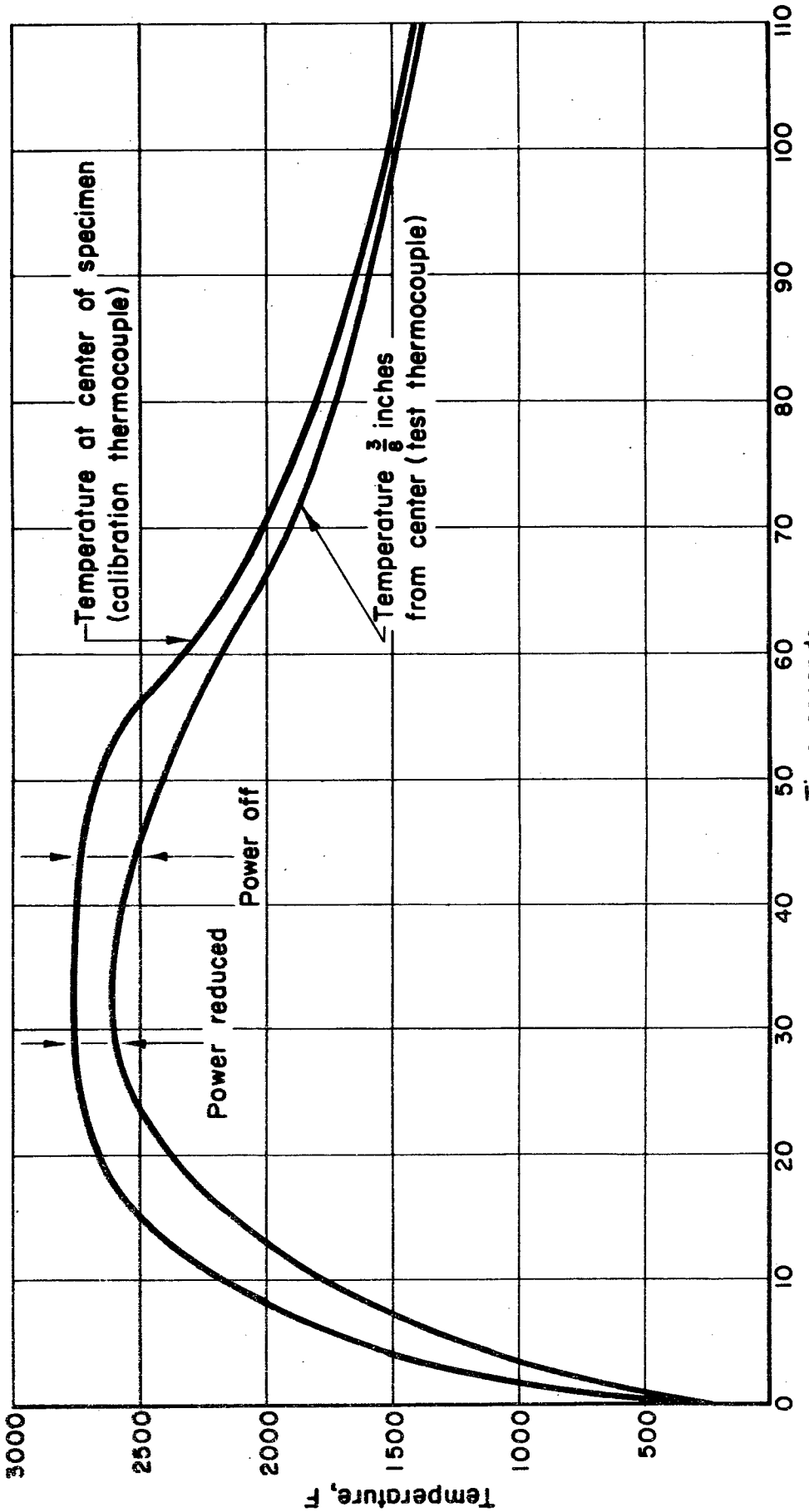

FIGURE 5. TEMPERATURES ATTAINED DURING HEATING AND COOLING OF SAE 4340 STEEL SPECIMENS IN THE HIGH-TEMPERATURE TENSION TESTS

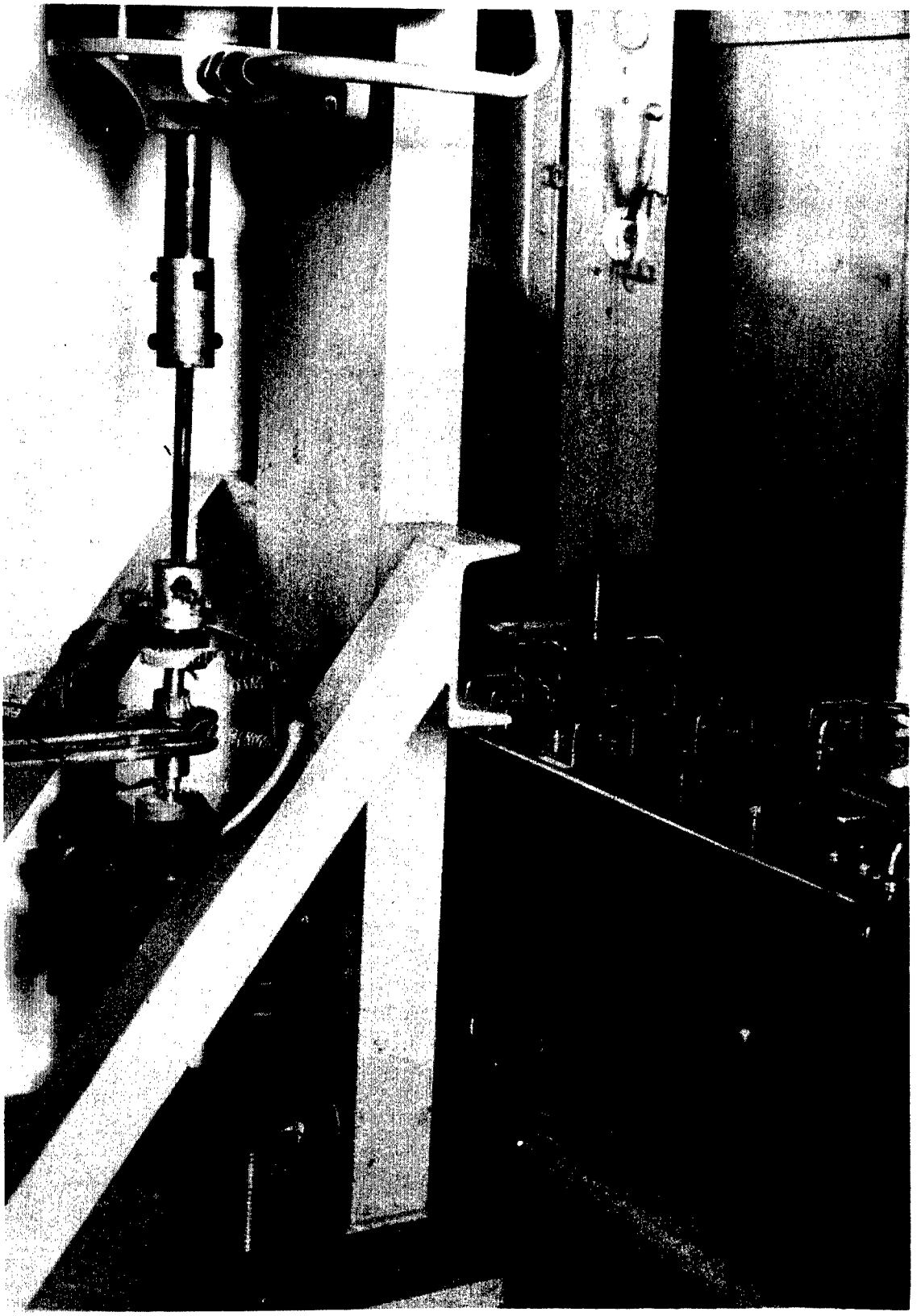

FIGURE 6. HOT-TENSION TEST ASSEMBLY AND INSTRUMENT USED TO RECORD STRESS AND ELONGATION

The device used to measure stress is shown in Figure 7. It is essentially a beam of hardened spring-steel plate, which is supported at each end and loaded at two points equidistant from the ends. Two SR-4 strain gages lie on the upper, or compression side of the plate, and two others, on the lower, or tension side. Differences in resistance between the upper and lower pairs are recorded on the Sanborn oscillograph recorder, shown in Figure 6. The stress-measuring device was calibrated on a 0 to 1000-pound tensile-testing machine. Readings were made in 5-pound increments throughout this range. Additional calibrating was done in the 1000- to 1350-pound range using a standard Battelle creep-test frame. Readings were taken in 50-pound increments. An advantage of the "weigh bar", as the stress-measuring device is called, is that it bridges the range of 0 to 5000 pounds repeatedly without showing any change in calibration.

A clip-gage extensometer was constructed for measuring strain. It consists of two hardened beryllium-copper clips, two SR-4 strain gages being attached to each one in the manner illustrated in Figure 8. The clips unbend as the specimen elongates, causing a change in resistance between the two outside gages connected in series and the two inside gages also connected in series. The resistance change is registered by the Sanborn oscillograph.

The clips were not allowed to form a complete circuit, as shown in Figure 8. In this way, they would not be heated as a result of the strong electrical field around the induction-heating coil. The clips were arranged so that they would slip off the brass points after the specimen had elongated 1 inch. The extensometer was calibrated with gage blocks available at Battelle.

Procedure and Results

Hot-tension tests were made on a series of SAE 4340 and SAE 1018 steel specimens in the temperature range 2588 F to 1800 F, during cooling from the melting temperature. The tests using SAE 4340 were conducted at 100 F increments. Specimens of SAE 1018 were derived from two different lots of cold-rolled plate. Those obtained from the first lot were tested at 2400 F, 2300 F, 2200 F, 2100 F, 2000 F, 1900 F, and 1800 F; the others were tested at 2588 F, 2407 F, 2256 F, 2135 F, 1968 F, and 1875 F.

Data are listed in Table 1 and plotted in Figure 9. Strengths were calculated using cross-sectional area at the temperature of load application.

Both types of steel have little or no strength and ductility at high enough temperatures. They show gains in the two properties with decreasing temperature, the gain in strength being especially rapid. For the most

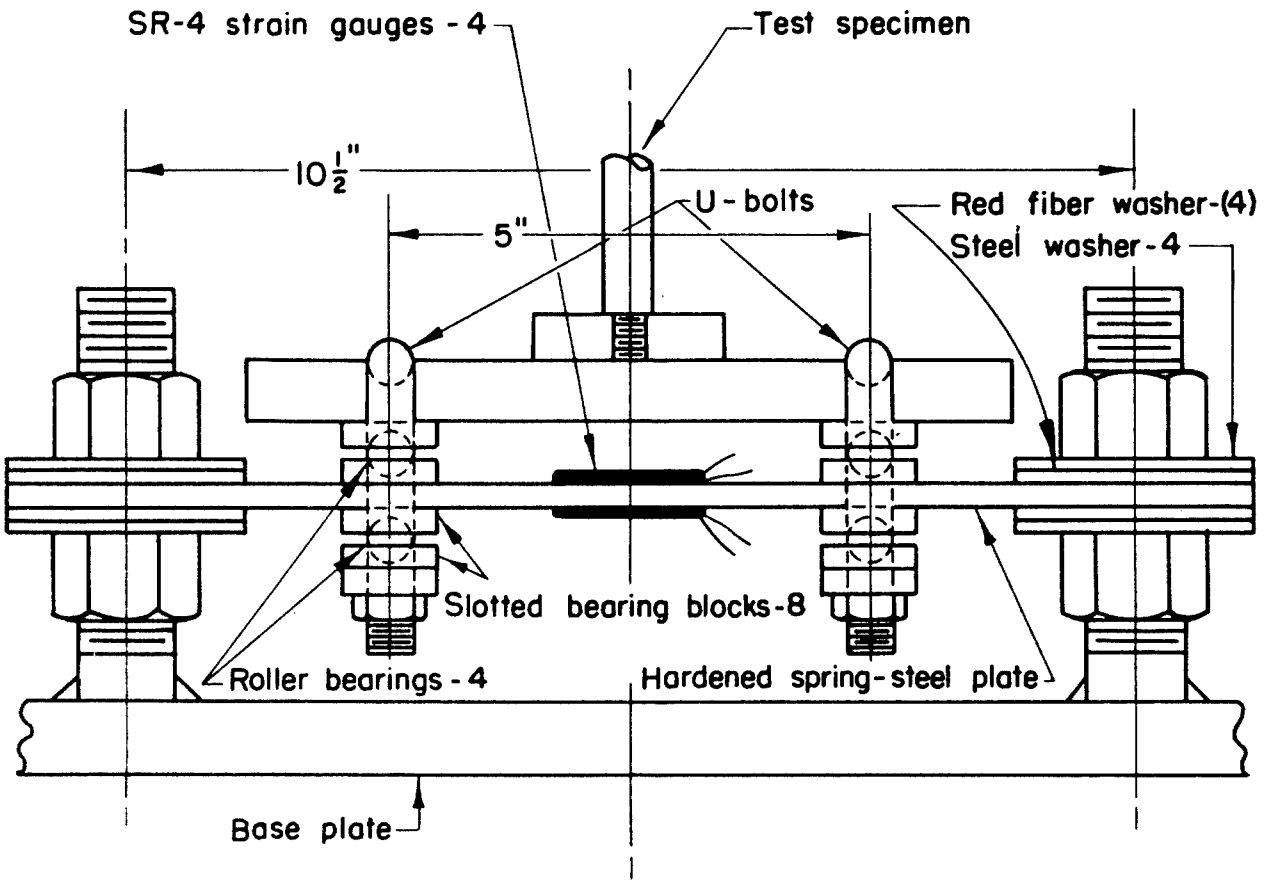

FIGURE 7. FOUR-POINT BEAM-LOADED DEVICE USED FOR MEASURING STRESS IN HOT-TENSION TESTS

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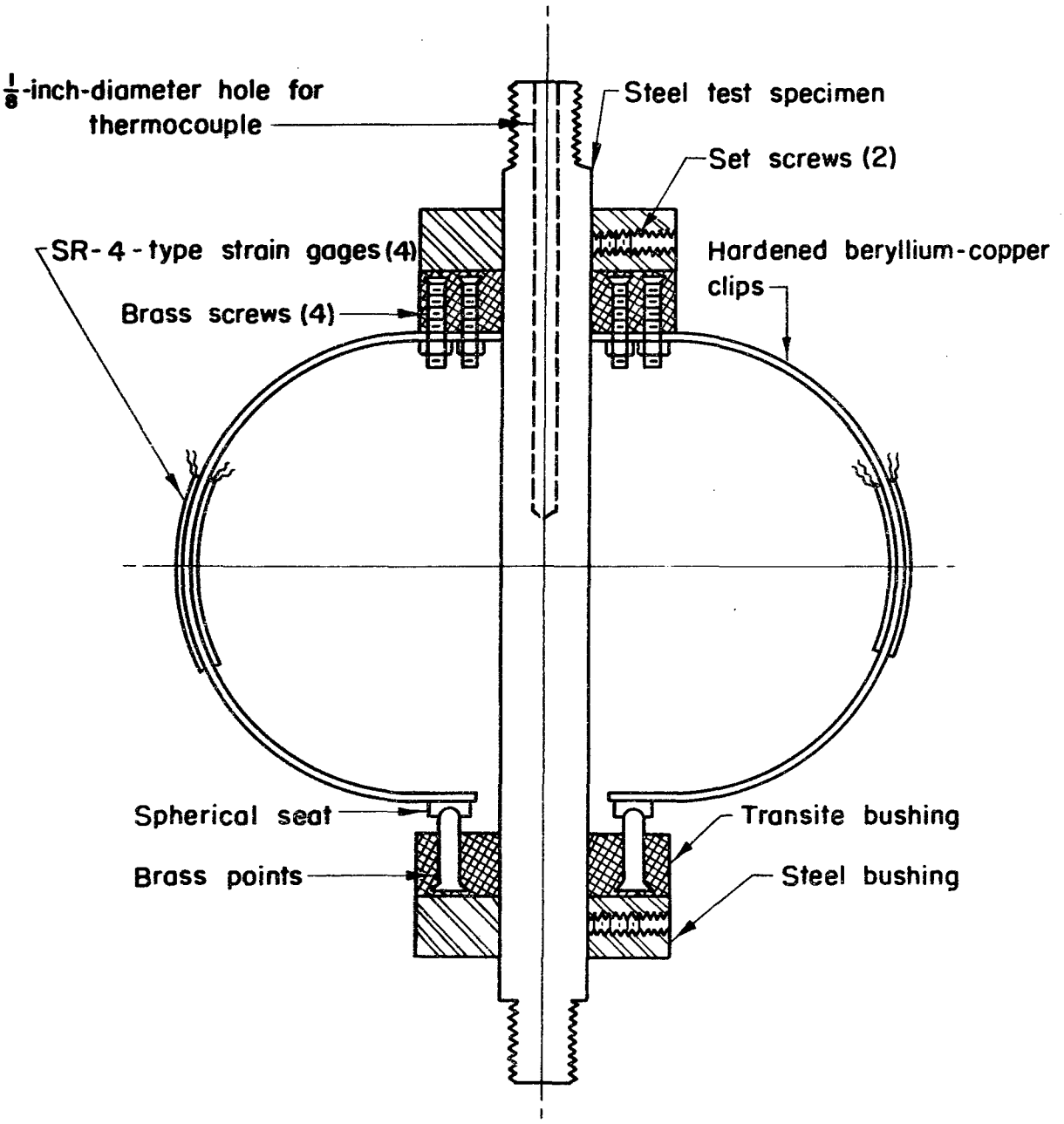

FIGURE 8. DETAILS OF CLIP-GAGE EXTENSOMETER USED FOR MEASURING ELONGATION IN HOT-TENSION TESTS

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TABLE 1. HOT-TENSILE PROPERTIES OF SAE 4340 AND SAE 1018 STEELS

Temperature, F	Elongation, inch		Strength, psi	
	SAE 4340	SAE 1018	SAE 4340	SAE 1018
2588		0.015		241
2407		0.111		>5755
2400	0.010*	0.000	726*	<209.9
2300	0.026	0.009	4010	3340
2256		0.084*		6480*
2200	0.024	0.038	3870	>5070
2135		0.084*		7280*
2100	0.162	0.030*	>5250	5380*
2000	0.270	0.032	>6330	>5880
1968		0.100*		>7280*
1900	0.213	0.018	>5855	>6330
1875		0.100*		7280*
1800	0.243	0.028	>6000	>6375

*Results of single tests. Other values are averages obtained from two or more tests.

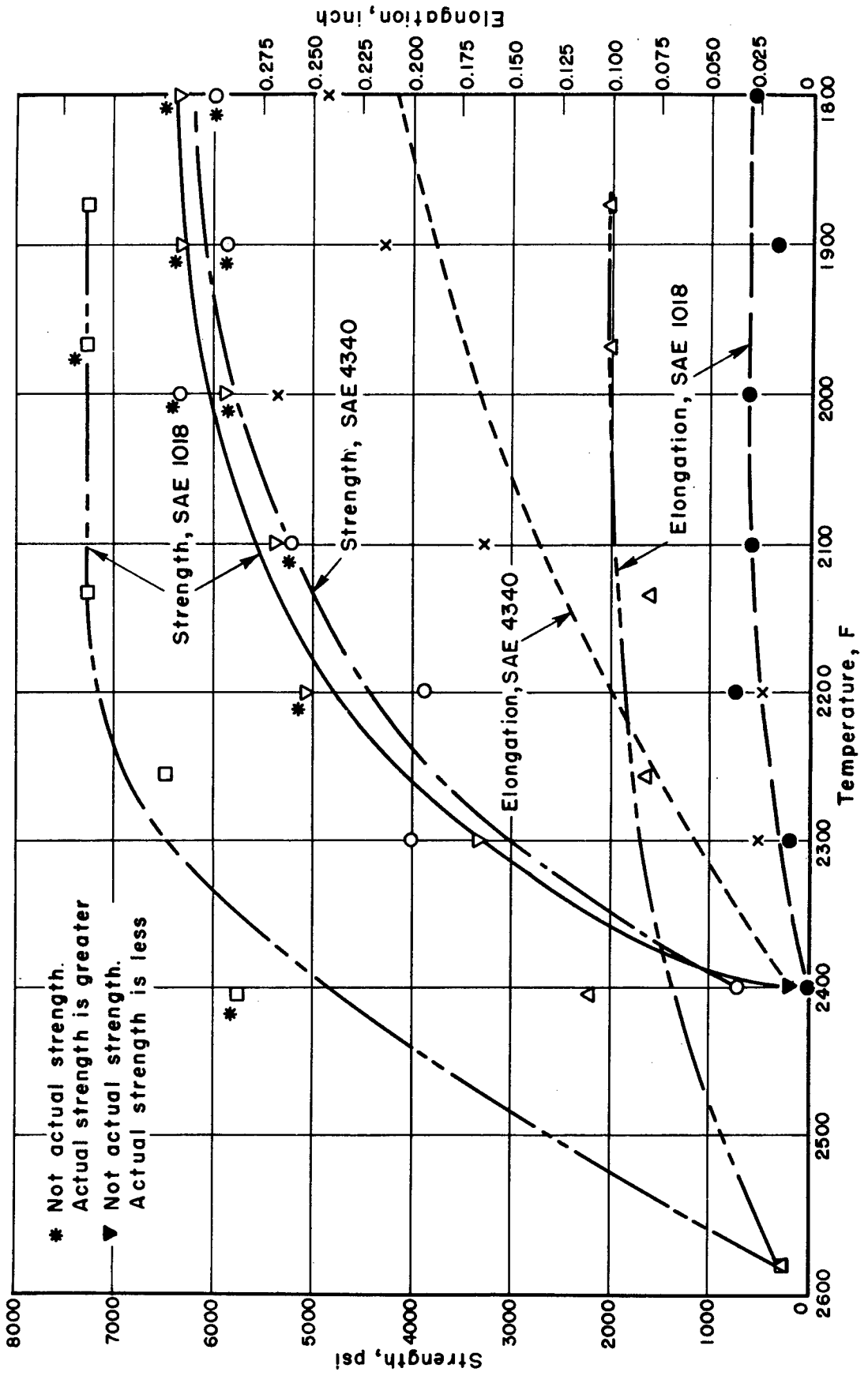

FIGURE 9 HOT-TENSILE PROPERTIES OF SAE 4340 AND SAE 1018 STEELS A-2919

part, SAE 1018 is stronger and less ductile than SAE 4340 in the temperature range 2400 F to 1800 F. Differences which appear between the two lots of SAE 1018 can probably be accounted for on the basis of compositional variations. Further work will be done to follow up this point. If differences can be explained by composition, this will support the basic ideas of this type of test.

On the basis of the results shown in Figure 9, since the SAE 1018 steel has much lower hot ductility than the SAE 4340 steel, it is anticipated that this steel would give much more cracking than SAE 4340 steel if it were used as a weld metal. Tests to follow up this point and establish basic correlation are in progress.

The good reproducibility of results obtained so far indicates that the hot-tension apparatus is working satisfactorily.

Hot-tension testing of steels prepared from high-purity electrolytic iron has been started. Similar studies will be conducted on specimens taken from high-strength welds deposited with commercial electrodes. An attempt will be made to extend the testing range upward; the lower limit of 1800 F will be maintained.

WELD-METAL CRACKING TESTS

A search was made of the literature for tests which might be useful in comparing the cracking susceptibility of high-strength weld-metal deposits. A test of this type was needed for studies in conjunction with hot-ductility tests of weld metals. Most welds deposited with high-strength electrodes are crack sensitive, but some are much more sensitive than others. It was desirable, therefore, to select a test which would show small variations in the degree of cracking. A circular-groove and a circular-patch test seemed to be the most promising on the basis of published data. A recently developed double-fillet test reported in the British literature also showed interesting results. A series of tests was made to evaluate these tests for studying the cracking propensity of commercial high-strength electrodes.

Electrodes

Four commercial high-strength electrodes were selected for the initial studies. Weld metal deposited with these electrodes had the following composition according to their manufacturers.

Electrode	Chemical Composition, per cent								
	C	Mn	Si	Cr	Ni	Mo	V	S	P
A	0.20	0.40	0.35	2.15	-	1.0	-	-	-
B	0.12	0.45	0.20	0.45	1.70	0.75	0.20	0.03 max.	0.03 max.
C	0.14	0.75	0.48	0.95	1.75	0.80	0.18	-	-
D	0.12	1.00	0.50	1.20	1.30	0.60	0.13	-	-

Double-Vee Butt-Joint Specimen

A few early tests were made with a straight-groove double-vee butt-weld specimen which was restrained in a jig. The jig, however, failed to produce the restraint necessary to cause even the most crack-sensitive weld metal to crack. In later tests, the desired restraint was attained by first welding heavy restraining plates to each end of the double-vee groove and then depositing the test weld. The results of tests with this specimen indicate that welds deposited with Electrodes A and B were crack sensitive. Welds deposited with Electrode C were relatively free of cracking. Test results with this specimen were not reproducible, probably because the restraint produced by the restraining plates could not be maintained constant. No further tests were made with the double-vee butt-joint specimen.

Circular-Groove Specimen

The circular-groove specimen was designed to produce maximum restraint on the weld metal without introducing a notch effect. It consists of a simple circular groove with tapering scarves and a rounded bottom cut into the surface of a 2-inch-square plate. The specimen is shown in Figure 10.

In the circular-groove test, the speed of welding is maintained at a rate of 5 inches per minute by use of a rotating jig. A single pass is deposited three-fourths of the way around the groove using one 5/32-inch-diameter electrode. Test results with four commercial high-strength welds deposited in SAE 4340 steel specimens are shown in Table 2. In one test, Weld Metal A cracked more than the other welds tested. The repeat test, however, did not confirm this result. In general, the results of the circular-groove cracking test were inconclusive, since they failed to show any significant differences among the four types of weld deposits.

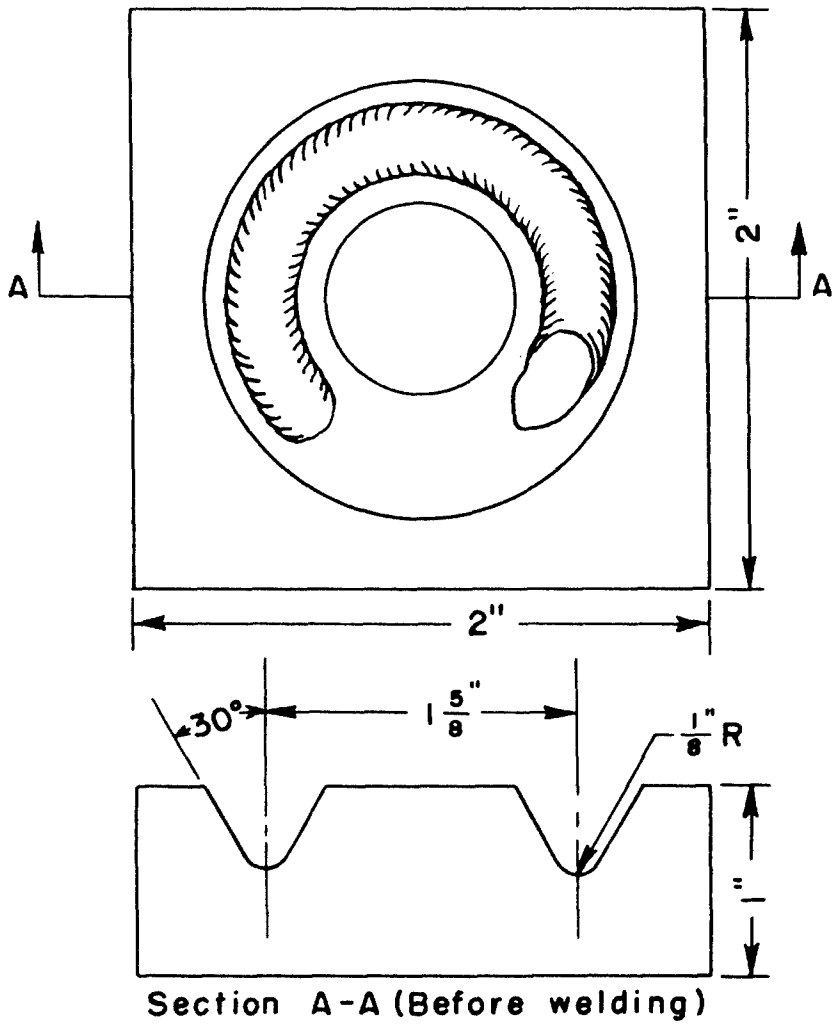

FIGURE 10. CIRCULAR-GROOVE TEST SPECIMEN

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TABLE 2. RESULTS OF WELD-METAL CRACKING TESTS USING CIRCULAR-GROOVE SPECIMENS OF SAE 4340 STEEL

Electrode	Crack Length, inches	
	Test 1	Test 2
Smooth Groove		
A	1 1/16	1/4
B	3/8	1/4
C	1/4	7/8
D	3/8	1/4
Notched Groove		
A	5/16	(1)
C	1/4	(1)

(1) No test made.

A 1/16-inch-wide by 1/8-inch-deep root notch was machined into the groove of two circular-groove specimens to increase severity. As shown in Table 2, the notch did not increase the degree of cracking as expected.

Circular-Patch Specimen

Weld-metal cracking tests were also made using a circular-patch specimen. This specimen is shown in Figure 11. The severity of the circular-patch test is greater than that of the circular groove because of the added effect of the root spacing.

In conducting this test, four beads are deposited in the sequence shown in Figure 11. A copper backup ring is used, so that each succeeding weld has correspondingly higher restraint.

The results of tests with circular-patch specimens are shown in Table 3. A high degree of cracking was obtained with the circular-patch specimen, but the test did not show the desired sensitivity to small variations in cracking susceptibility.

Double-Fillet Hot-Cracking Test

A recently developed double-fillet hot-cracking test[1] was tried with Weld Metals A and C. The test specimens consist of two members, as shown in Figure 12. The top member was used in three different widths, 1 inch, 1-1/2 inches, and 2 inches, depending on the severity of test required. The wider the top plate, the more severe the test.

The restraining weld, shown on the left side of Figure 12, was made with an austenitic electrode for increased test severity. The test weld (Figure 12) was started 6, 5, or 4 seconds after the restraining weld, according as the width of the top member was 1 inch, 1-1/2 inches, or 2 inches, respectively. Both welds were laid down in the same direction.

The results of tests using Electrodes A and C and SAE 4340 base metal are shown in Table 4. The least severe test with Electrode A will have to be repeated.

The test is apparently too severe. Further tests will be conducted with Weld Metals A, B, C, and D. Then, if necessary, modifications designed to reduce the severity of the test will be made.

(1) Hinds, E. G. P., "A New Double-Fillet Test for Hot-Cracking", Welding Research, Vol. 6, February, 1952, pp. 27r-28r.

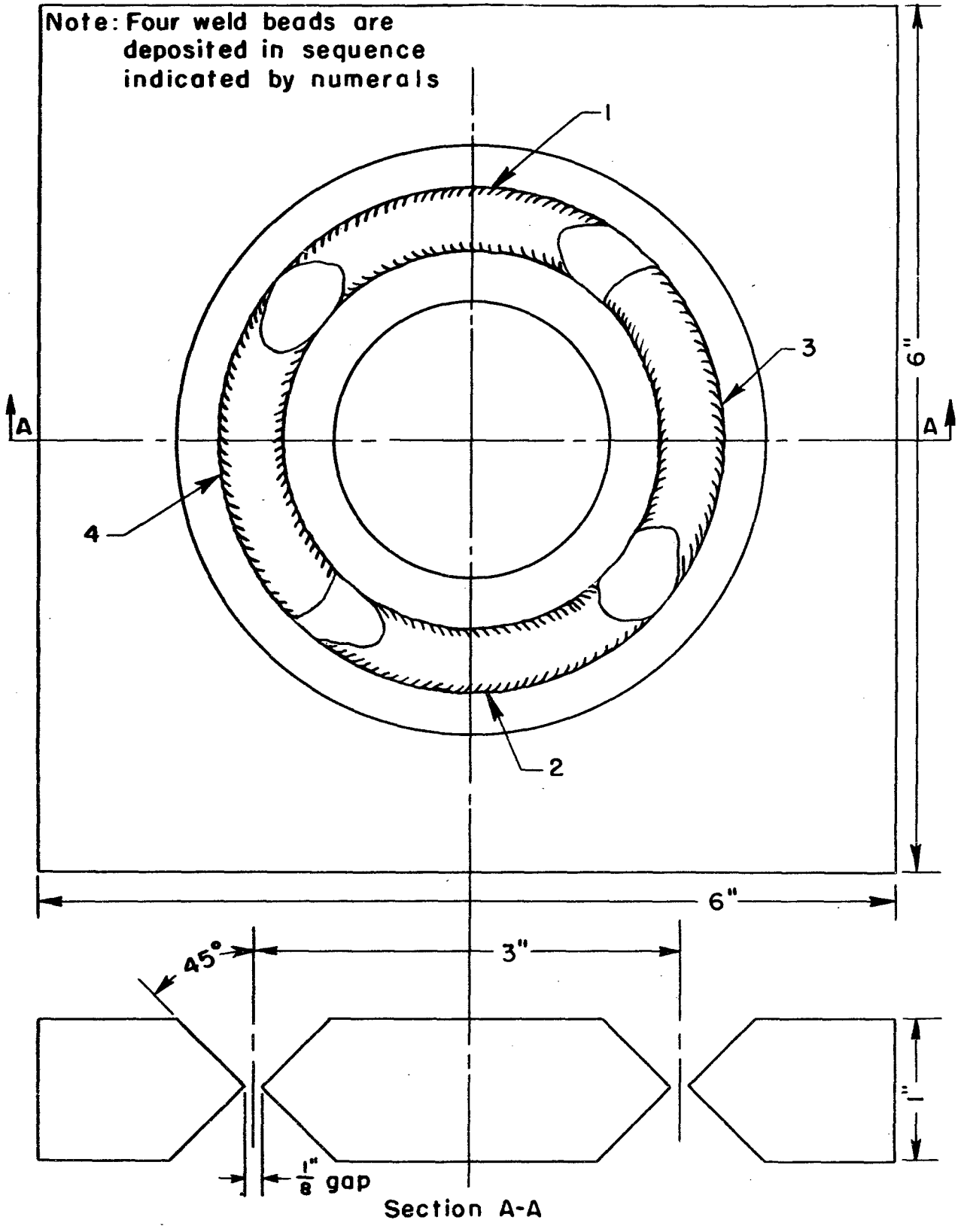

FIGURE 11. CIRCULAR-PATCH TEST SPECIMEN

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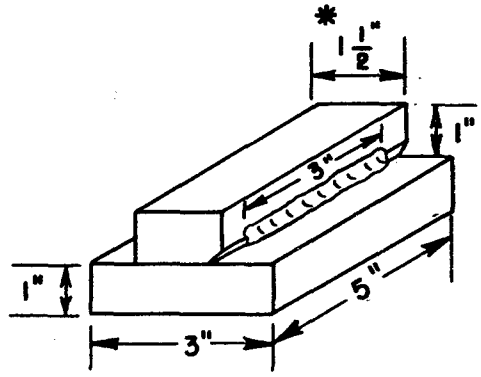
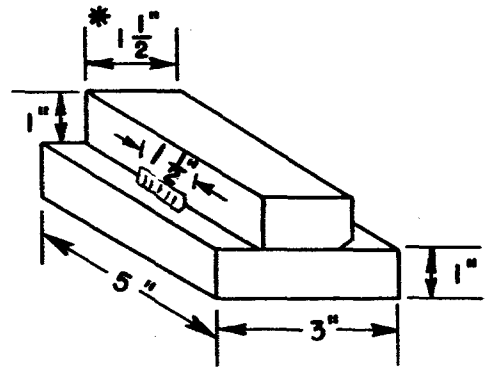
TABLE 3. RESULTS OF CIRCULAR-PATCH TESTS OF WELD METAL DEPOSITED IN SAE 4340 STEEL

Electrode	Bead No.	Cracking, per cent of bead length	
		Test 1	Test 2
A	1	64	32
	2	16	64
	3	16	64
	4	21	75
B	1	21	(1)
	2	85	(1)
	3	43	(1)
	4	43	(1)
C	1	43	59
	2	96	48
	3	27	48
	4	27	43
D	1	48	(1)
	2	100	(1)
	3	21	(1)
	4	37	(1)

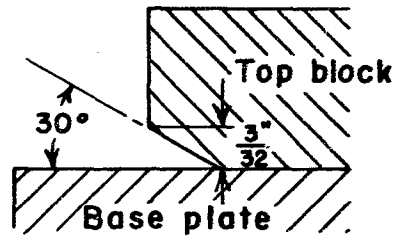
(1) Test not made.



Restraining weld



Test weld



Enlarged view of chamfered edge (end-on view)

*Depends on severity of test

FIGURE 12. DOUBLE-FILLET TEST SPECIMEN

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TABLE 4. RESULTS OF DOUBLE-FILLET TESTS OF WELD METAL DEPOSITED IN SAE 4340 STEEL

Electrode	Severity Level, inch	Cracking
A	1-1/2	Crack along length of test weld
	2	Crater cracks only
C	1	Crack along length of test weld
	1-1/2	Crack along length of test weld
	2	Crack along length of test weld

EXPERIMENTAL HEATS OF HIGH-PURITY STEELS

On the basis of the literature, sulfur is more closely associated than any other element with weld-metal hot cracking. It is believed that a crack will initiate at any point where a critical concentration of sulfur is present. Consequently, the fact that sulfur is kept within specification limits may be no guarantee against cracking.

The best way to check whether sulfur is a major factor in weld-metal cracking would be to prepare a sulfur-free steel and weld it with sulfur-free electrodes. It was not possible, however, to make sulfur-free steel with materials now available. The lowest percentage sulfur that could be anticipated was 0.003 to 0.005, but any percentage less than 0.005 probably would have little or no influence on weld-metal cracking. Most of it would be dissolved in alpha ferrite, in which form it would show little tendency to segregate.

Seven SAE 43XX heats were made to use in hot-ductility and hot-cracking tests. All but one had sulfur compositions of 0.008 per cent or less.

Materials

The basic material in all of the heats was commercial-grade electrolytic iron containing 0.007 per cent sulfur. By hand picking clean flakes of iron from badly coated pieces, a small amount of 0.003 per cent sulfur iron

was obtained. A pickling operation with dilute hydrochloric acid was employed to remove the coating from the remaining iron. The desired product contained 0.005 per cent sulfur.

All other materials used in these heats had negligible sulfur contents.

Procedure and Results

An induction furnace with a magnesia crucible and an argon atmosphere was used for all heats. Contamination from furnace linings, mold washes, and the laboratory atmosphere was carefully guarded against.

The compositions of the seven heats are shown in Table 5. Numbers 1 through 4 were 100-pound melts, and the remainder were 50-pound melts. Heats Nos. 1, 2, and 3, with carbon contents of 0.30, 0.40, and 0.50 per cent, respectively, were prepared for studies on the effect of carbon on the cracking susceptibility of high-purity steel. Heat No. 4 was a normal SAE 4340 steel to be used as a standard.

Heats Nos. 5 and 6 were treated with lime-fluorspar and lime-alumina slags, respectively, in an attempt to reduce the sulfur content. The slag was added to the molten electrolytic iron, held for 5 minutes, and then skimmed off. This operation was repeated three times for each heat. It is evident from Table 5 that the treatment was unsuccessful in lowering sulfur. The phosphorus content was reduced.

Three pounds of misch metal were added per ton of Heat No. 7, which had been aluminum killed. Misch metal contains approximately 55 per cent cerium, 40 per cent lanthanum, and 2 per cent iron. The addition of this material to ingots has reduced hot cracking, probably by changing sulfur to a harmless form. Misch metal would be expected similarly to lessen weld-metal cracking.

One-half of each heat was forged and rolled into 1-inch-thick plate for use as base plates in weld-cracking tests. The other half was rolled into 3/4-inch and 1/4-inch rounds for use as hot-strength specimens and welding wire, respectively.

ELECTRON-MICROSCOPE STUDIES OF WELD METAL

The survey of the literature on weld-metal cracking pointed out that most weld-metal cracking is interdendritic or intergranular. The electron

TABLE 5. COMPOSITION OF EXPERIMENTAL SAE 43XX TYPE STEELS

Heat No.	Chemical Composition, per cent							
	C	Mn	Si	Ni	Cr	Mo	S	P
1	0.33	0.76	0.26	1.91	0.83	0.25	0.005	0.008
2	0.45	0.64	0.33	1.88	0.82	0.26	0.008	0.005
3	0.59	0.66	0.29	1.93	0.81	0.26	0.006	0.007
4	0.46	0.66	0.20	1.94	0.83	0.26	0.037	0.026
5	0.46	0.77	0.25	1.89	0.90	0.24	0.008	0.004
6	0.46	0.69	0.21	1.83	0.82	0.21	0.006	0.004
7(1)	0.45	0.72	0.07	1.92	0.88	0.24	0.006	0.007

(1) 3 lbs per ton of misch metal added.

microscope was used to study the area between dendrites and grain boundaries, in an attempt to identify any structure(s) which might be causing the cracking. Magnifications as high as 16000X were obtained.

Weld-Metal Specimens

Three commercial high-strength electrodes were used in the preparation of weld-metal specimens. These were the electrodes designated as A, B, and C in the preceding section on weld-metal cracking tests. Electrodes A and B were seen to be crack sensitive, and Electrode C was relatively crack free, according to tests with the double-vee butt-joint specimen.

Weld Specimens A and C were deposited without restraint and had no cracks. Weld B was restrained when deposited and contained a large shrinkage crack and many small cracks running in the direction of the columnar grain boundaries, as shown in Figure 13.

Examination Technique

The polishing of specimens was accomplished on wet abrasive paper and on wax wheels coated with alumina. The specimens were etched either in a 1 per cent nitric acid-alcohol solution for 35 seconds or in a solution of 1 per cent picric acid plus 2.4 per cent hydrochloric acid in alcohol for 15 seconds. Neither etchant stains the sample. Alcohol rinsing and drying in a warm-air blast followed etching.

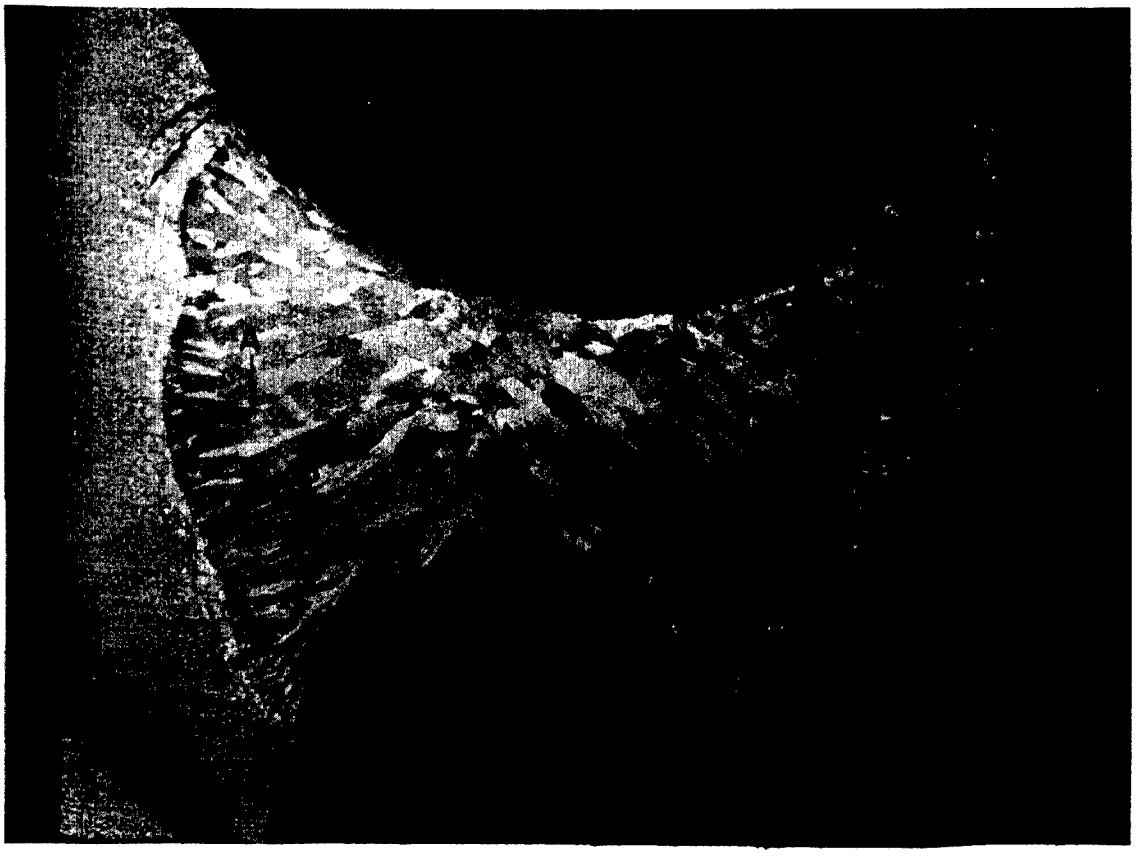
Any specimen subjected to electron-microscopic examination must be about 0.1 micron or less in thickness. Hence, in the case of a metal, it is necessary to prepare a replica of the etched surface. If an etchant leaves a stain, replica pickup will confuse the electron micrograph.

A two-stage positive-replica method was used in this investigation.(2) Two replicas were made, the first, a thick negative one of Zapon* which had been dried on the etched surface, the second, an approximately 0.005 micron thick positive of Formvar** which had been cast from ethylene dichloride solution on the stripped Zapon replica. The positive Formvar replica was freed for examination by selectively dissolving the Zapon in

(2) Austin, A. E., and Schwartz, C. M., "Modification of a Positive Replica Technique for Electron Microscope", Jour. Applied Physics, V. 22, June, 1951, pp. 847-848.

* Nitrocellulose lacquer.

** Polyvinyl formal.



8X Picral Plus 3 Per Cent HCl Etchant 90843

(A) Cracks along columnar grains
(B) Shrinkage crack
(C) Underbead cracks

FIGURE 13. LIGHT MACROGRAPH OF RESTRAINED WELD DEPOSITED WITH ELECTRODE B

amyl acetate. For contrast enhancement, the Formvar replicas were shadowed with 0.001-micron-thick platinum, vacuum evaporated at incidence angle arc tangent 2.

Light micrographs of the specimens were taken at 8X magnification to show the appearance of the weld sections, and at 100X magnification for correlation with electron micrographs.

Results

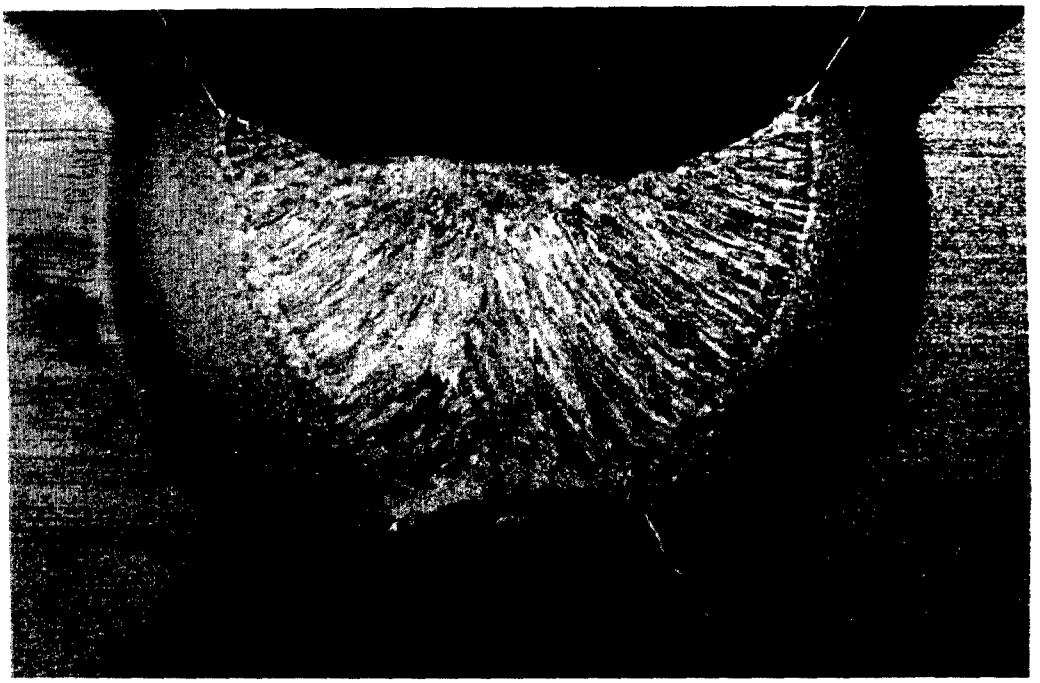
Low-magnification light micrographs of weld metal deposited with Electrodes B, A, and C are shown in Figures 13, 14, and 15, respectively. High-magnification light micrographs are shown in Figure 16. Figures 17 through 25, inclusive, portray electron micrographs.

Figures 13, 14, and 15 show columnar grains meeting in the center of the weld. This area was studied in more detail, because it is the most frequently observed site of cracking. Figure 13 shows the large shrinkage crack and the small cracks running in the direction of the columnar grain boundaries, to which reference has already been made.

Figure 16 illustrates the central zone of all three weld deposits at higher magnifications. The light grain boundaries, which were interpreted as the remnants of the boundaries of the primary solidification grains, seem to be broader in the more crack-susceptible Weld Metals A and B. Cracks of both the intergranular and transgranular varieties appear in Weld Metal B.

The electron micrographs, shown in Figures 17 through 25, also were taken of areas in the central zone of Weld Metals A, B, and C. Figures 17 and 18 support the observation made in Figure 16 that Weld Metals A and B have more prounounced grain boundaries than Weld Metal C. In addition, Figures 17 and 18 show that the grain boundaries did not etch so deeply as the surrounding metal, in this way suggesting a compositional difference. Nor are the boundaries precisely delimited from the grains; instead they gradually merge into the grains. They may not be true grain boundaries at all, but rather a composition variance resulting from segregation which occurred when the grains were formed. The high magnification and extremely small-screen openings employed in the electron-microscope studies made it difficult to distinguish the columnar grain boundaries from the area between dendrite branches within the columnar grains.

Figures 19 and 21 illustrate the fine boundaries of large prior austenite grains in Weld Metals A and C, respectively. The boundary in Weld Metal A was continuous for about 150 microns before junction with similar boundaries. The boundary in Weld Metal C was continuous for more than 150 microns. Figures 20 and 22 show portions of these

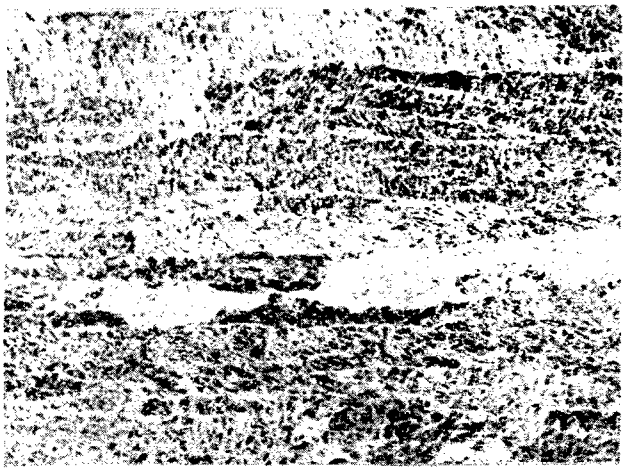


8X Picral Plus 3 Per Cent HCl Etchant 90726

FIGURE 14. LIGHT MACROGRAPH OF WELD DEPOSITED WITH ELECTRODE A SHOWING COLUMNAR GRAIN STRUCTURE

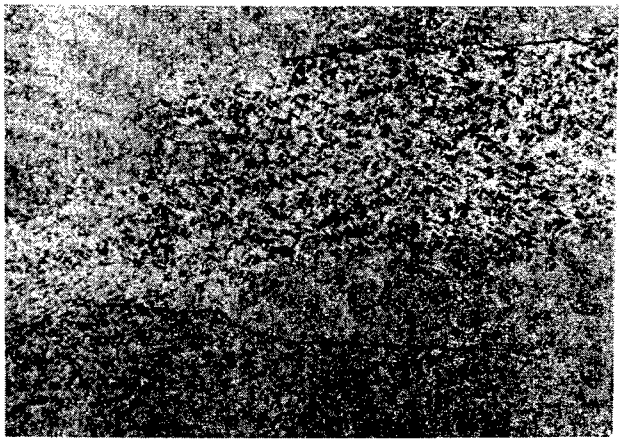
8X Picral Plus 3 Per Cent HCl Etchant 90725

FIGURE 15. LIGHT MACROGRAPH OF WELD DEPOSITED WITH ELECTRODE C SHOWING COLUMNAR GRAIN STRUCTURE



100X 90950

Weld Metal A



Cracks Tend to Follow Columnar Grain Boundaries

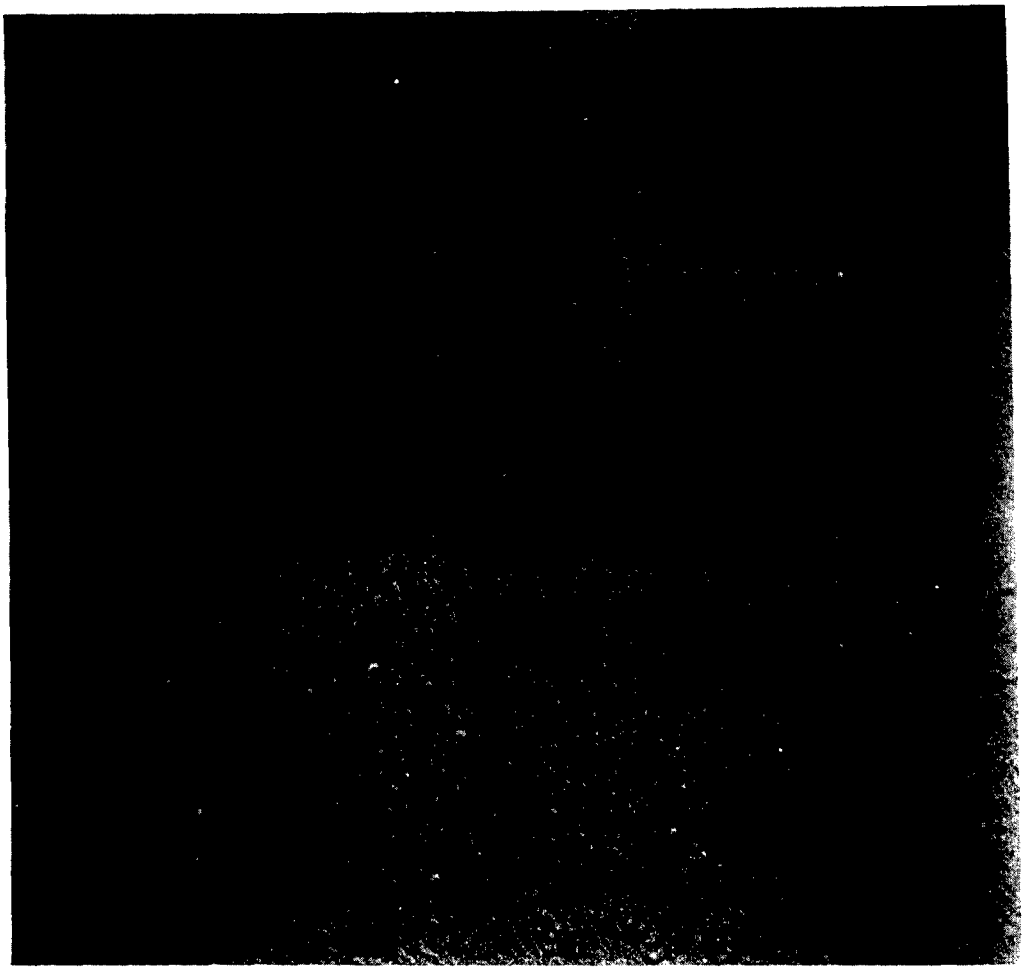
100X

Weld Metal B

100X Picral Plus HCl Etchant 90951

Weld Metal C

FIGURE 16. LIGHT MICROGRAPHS SHOWING COLUMNAR GRAIN BOUNDARIES IN WELDS DEPOSITED WITH HIGH-STRENGTH ELECTRODES



6500X Nital Etch E2748DR

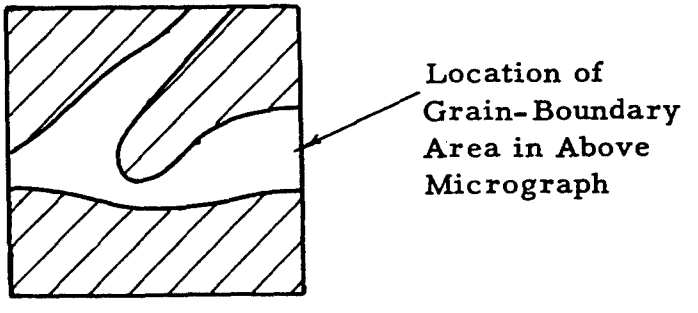


FIGURE 17. ELECTRON MICROGRAPH OF WELD METAL A ILLUSTRATING THE GRADUAL MERGING OF GRAIN-BOUNDARY AREAS INTO THE GRAIN

4000X Nital Etch E3240CR

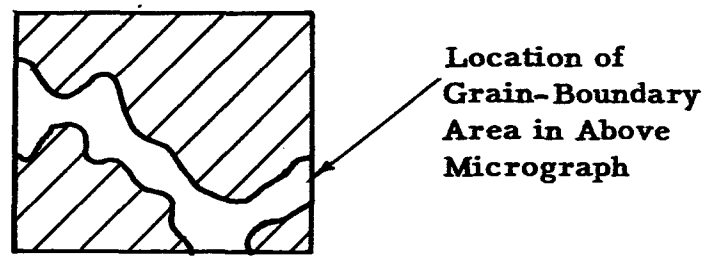
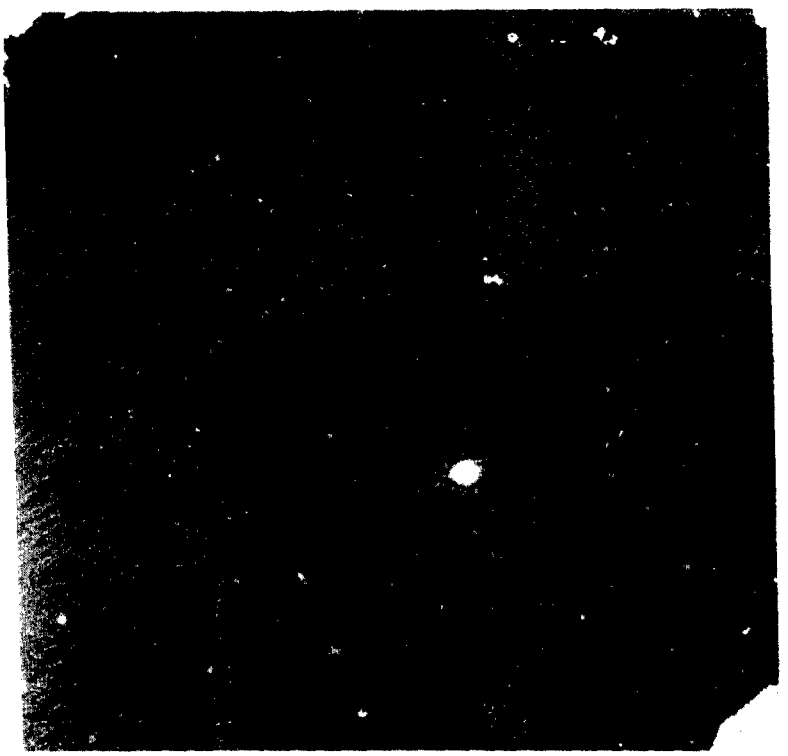


FIGURE 18. ELECTRON MICROGRAPH SHOWING WIDE GRAIN-BOUNDARY AREAS IN WELD METAL B



3200X Picral Plus HCI Etch E2873CR

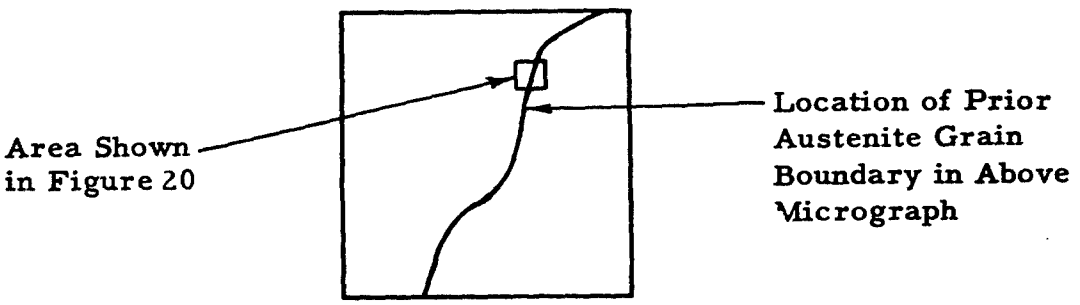
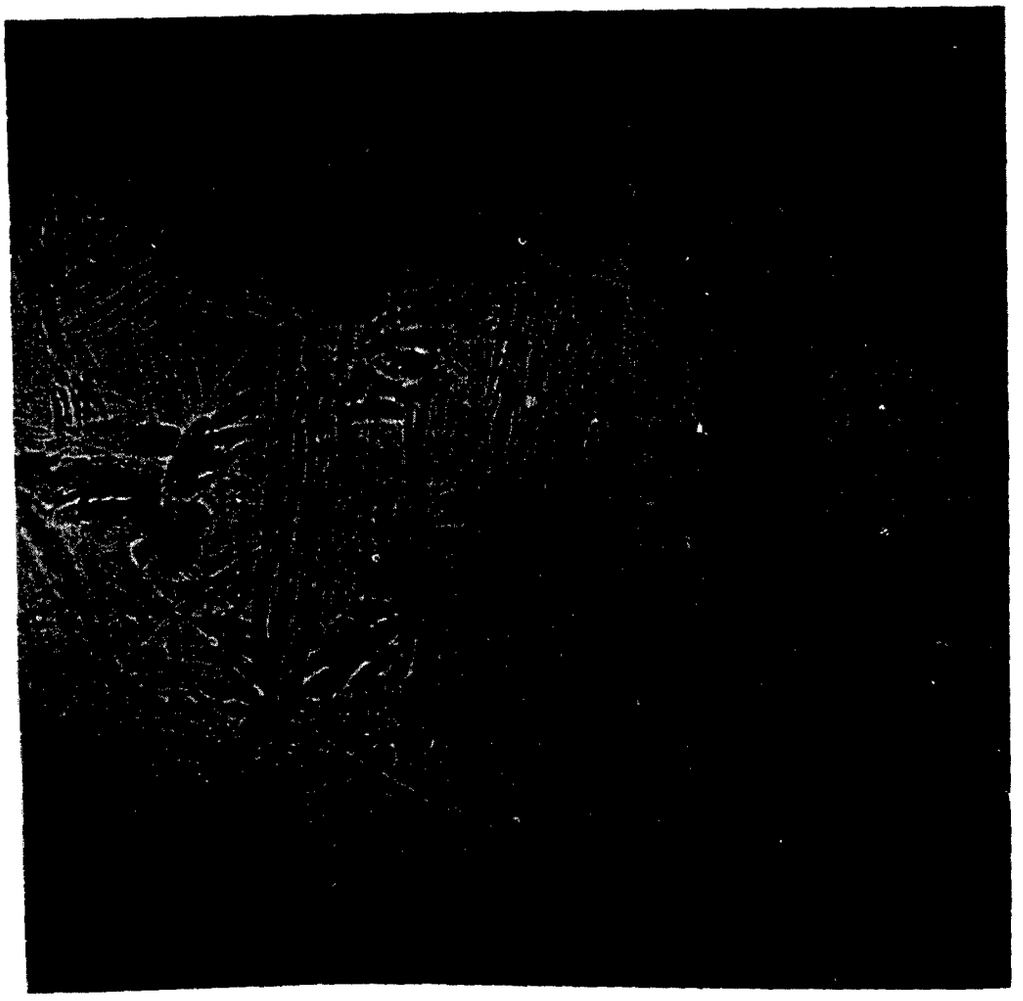


FIGURE 19. ELECTRON MICROGRAPH OF WELD METAL A SHOWING A FINE AUSTENITIC GRAIN BOUNDARY

16,000X Picral Plus HCl Etch E2873DR

FIGURE 20. ELECTRON MICROGRAPH OF WELD METAL A SHOWING UPPER PART OF AREA SHOWN IN FIGURE 19



3200X Picral Plus HC1 Etchant E2899BR

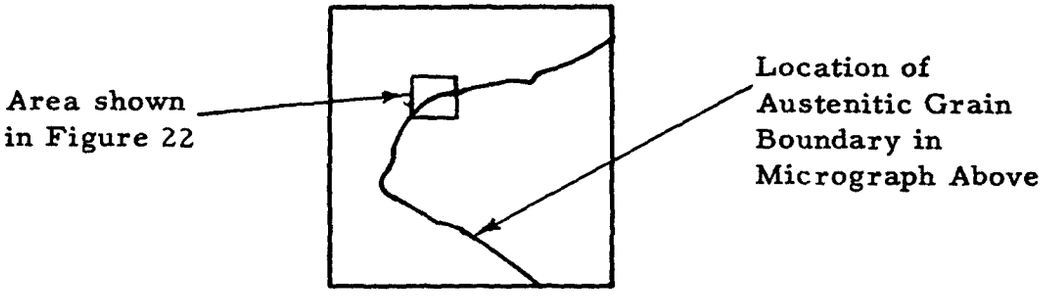
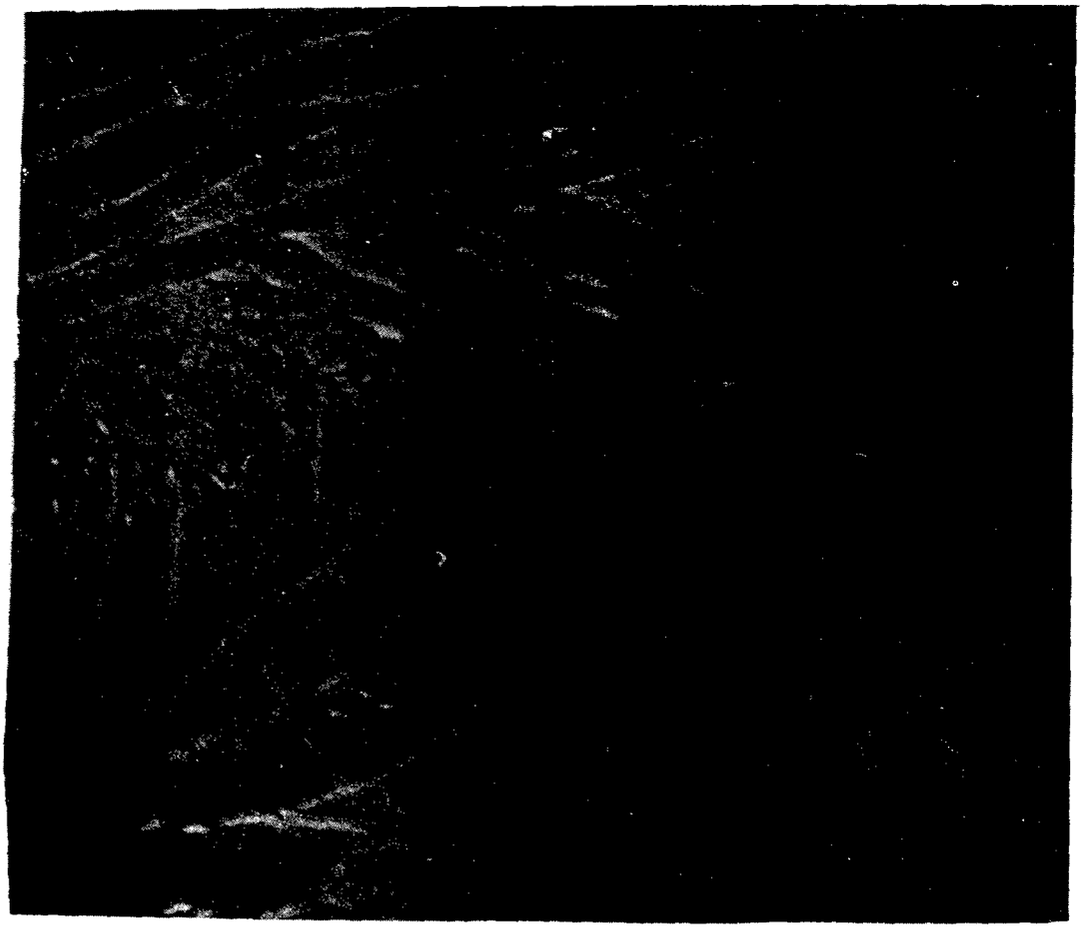


FIGURE 21. ELECTRON MICROGRAPH OF WELD METAL C ILLUSTRATING AUSTENITIC GRAIN-BOUNDARY STRUCTURE



16,000X E2899ER

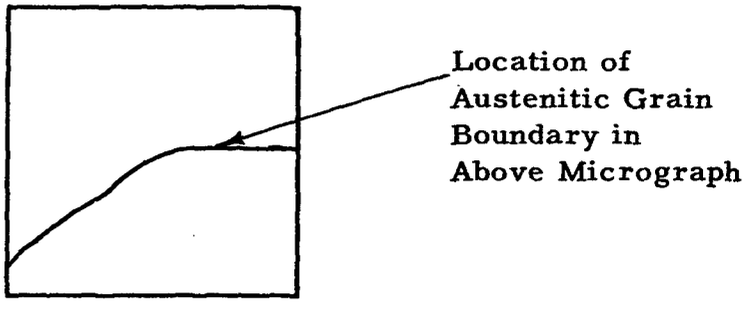
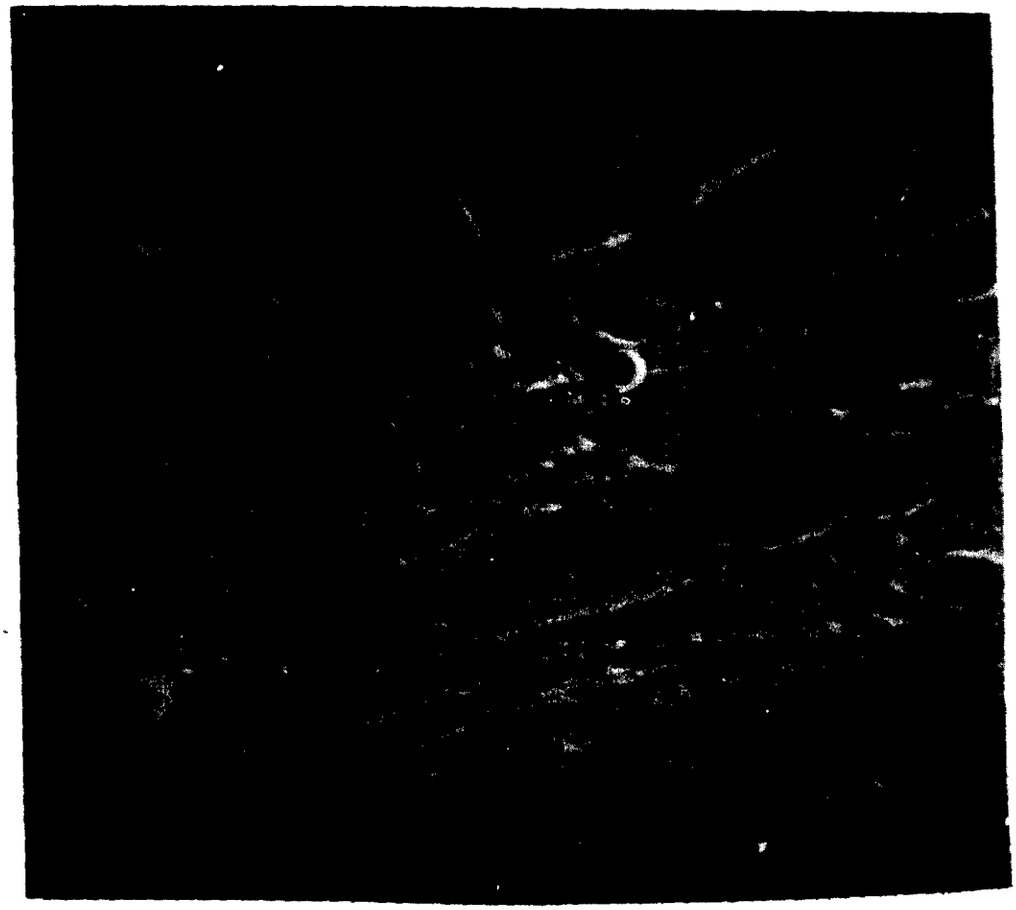


FIGURE 22. ELECTRON MICROGRAPH OF WELD METAL C SHOWING THE LEFT-CENTER PORTION OF FIGURE 9 AT HIGH MAGNIFICATION.

(The fineness of the boundary is revealed.)



16,000X Picral Plus HCl Etchant E2898DR

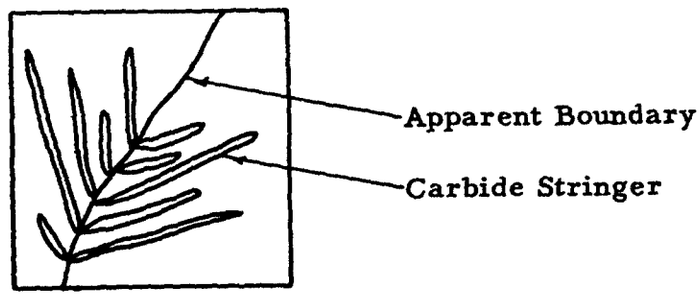
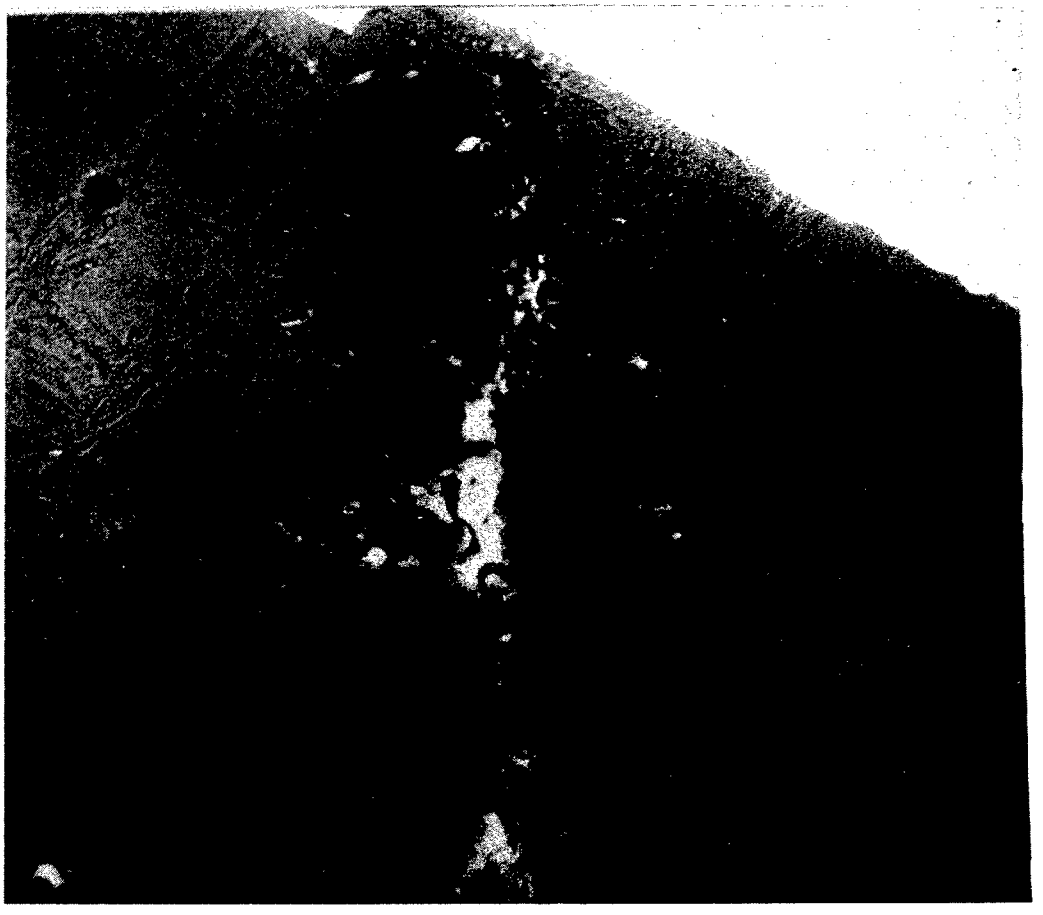


FIGURE 23. ELECTRON MICROGRAPH OF WELD METAL C SHOWING AN APPARENT BOUNDARY AS INDICATED BY A CHANGE IN THE PREFERRED ORIENTATION OF THE FERRITE



3200X Picral Plus HCl Etch E2997AR

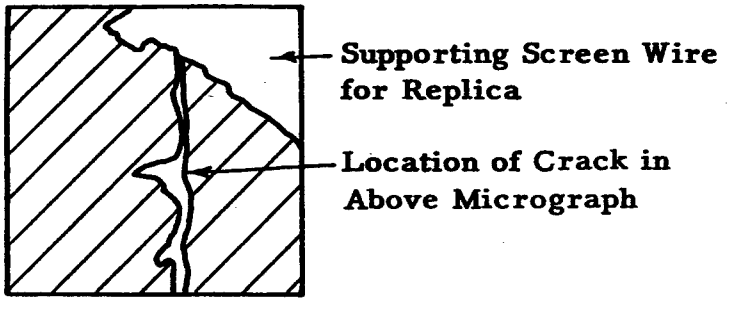


FIGURE 24. ELECTRON MICROGRAPH OF WELD METAL B SHOWING APPEARANCE OF CRACK

(The white clumps are debris picked up by the replica. Tearing of the replica occurred because the crack was too wide.)

16,000X Nital Etch E3025ER

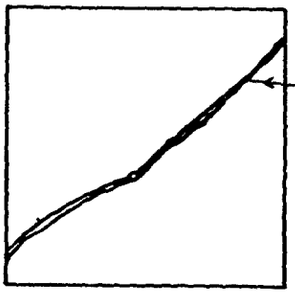


FIGURE 25. ELECTRON MICROGRAPH OF WELD METAL B SHOWING CRACK FINE ENOUGH TO BE REPLICATED READILY

(Note that the structure appears to cross the track.)

boundaries at much higher magnification. Figure 23 shows a section of an austenitic grain boundary in Weld Metal C which appears to be discontinuous, although the preferred orientation of the carbide stringers in the etched ferrite has changed in direction, indicating that a boundary did exist but may have been destroyed later by austenite-ferrite transformation.

Figure 24 shows a crack in Weld Metal B that was too wide for electron-microscope study. The replica tore at the crack edges and contained debris, possibly from polishing media, within the crack. Figure 25 shows a fine crack in the same specimen which was as narrow as 0.1 micron. In this case, the replica did not break. Cracks such as the two observed in Figures 24 and 25 were all transgranular.

Discussion of Results

The grain boundaries in crack-sensitive weld metals appear to be more prominent than the boundaries in crack-insensitive metals. The boundary areas may be segregates which formed during freezing of the weld metal.

The cracks observed in Weld Metal B were, for the most part, intergranular. There were many instances, however, in which they cut across grains.

The potential value of the electron microscope can be readily appreciated. Cracks that are not large enough to be resolved by the ordinary light microscope, can be studied over several hundred microns. It is entirely possible that the electron microscope will uncover structural changes in grain boundaries, which result from compositional variations in weld metal.

It will not be easy to find the origin of a crack, since the crack may propagate radially from its origin. Complete fracturing of the weld metal will be necessary. Examination of an entire crack surface by replication methods might indicate a correlation between occurrence of cracks and electron or light microscope evidence of flaws or inclusions. Inclusions may act as nuclei for cracks.

Hitherto, very little work had been done on studies of grain boundaries and cracks in high-strength ferritic weld metals. The electron-microscope studies, reported above, required a considerable expenditure of time in developing suitable techniques. The limited work completed and reported here shows that the electron microscope may be a valuable tool in future phases of this investigation when used in conjunction with the hot-ductility and hot-cracking data on various weld-metal compositions.

FUTURE WORK

Further hot-tension tests will be made to verify the results already obtained with SAE 4340 and SAE 1018 and to determine more closely the temperature zone of low strength and ductility for these two steels. After these tests, the high-temperature tensile properties of steels prepared from high-purity electrolytic iron and of high-strength welds deposited with commercial electrodes will be investigated. The effects of carbon and impurity elements, and of agents for minimizing the effects of impurities on these properties will eventually be studied.

Additional evaluation tests will be conducted in an attempt to obtain a reliable cracking susceptibility test. The circular-groove, circular-patch, and double-fillet tests will continue to be explored. The long-range object is to correlate the results of hot-tension tests with those of cracking-susceptibility studies.

The electron microscope will be used for examination of grain boundaries and cracks in weld metal when this type of study seems to be warranted. Electron-diffraction, microspectographic analysis, and radio-active tracer elements are potential supplements in such studies.